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GENERAL ELECTRIC CO PRINCETON NJ ASTROSPACE DIV
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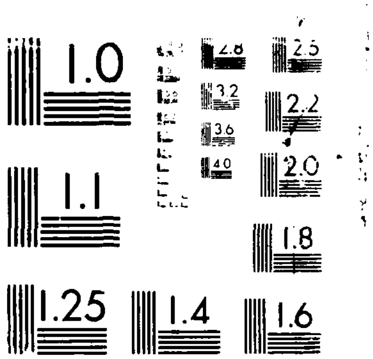
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 Astro Space

Heavy Ion and Proton Tests for Subsystem Upset

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HEAVY ION AND PROTON TESTS FOR SUBSYSTEM UPSET

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This report describes the results of heavy ion and proton tests for upset in a CMOS/SOS subsystem ALU (Arithmetic Logic Unit) which is part of a spacecraft computer. The Bevalac facility at Berkeley provided an iron spectrum with a maximum LET of 26 MeV-cm^2/mg, and the Tandem Van de Graaff at Brookhaven provided gold ions with a LET of 83 MeV-cm^2/mg at normal incidence. Protons of 180-MeV energy and 10-µs pulsewidths were obtained at the Brookhaven REF facility. Peak proton dose rates of 7.9E9 rads/s were delivered by micropulses of 1-ns width and with a period of 5 ns. Results showed that the ALU operated without upset during both heavy ion tests. However, functional failure of microprocessor devices occurred during proton irradiations; whereas RAM and MXR (Microprogram Controller and Sequencer) parts were not upset. A single pulse of 119 krads (Si) caused upset of the microprocessor, but multiple pulse doses of 19 to 60 megarads did not upset the RAM and MXR, respectively.

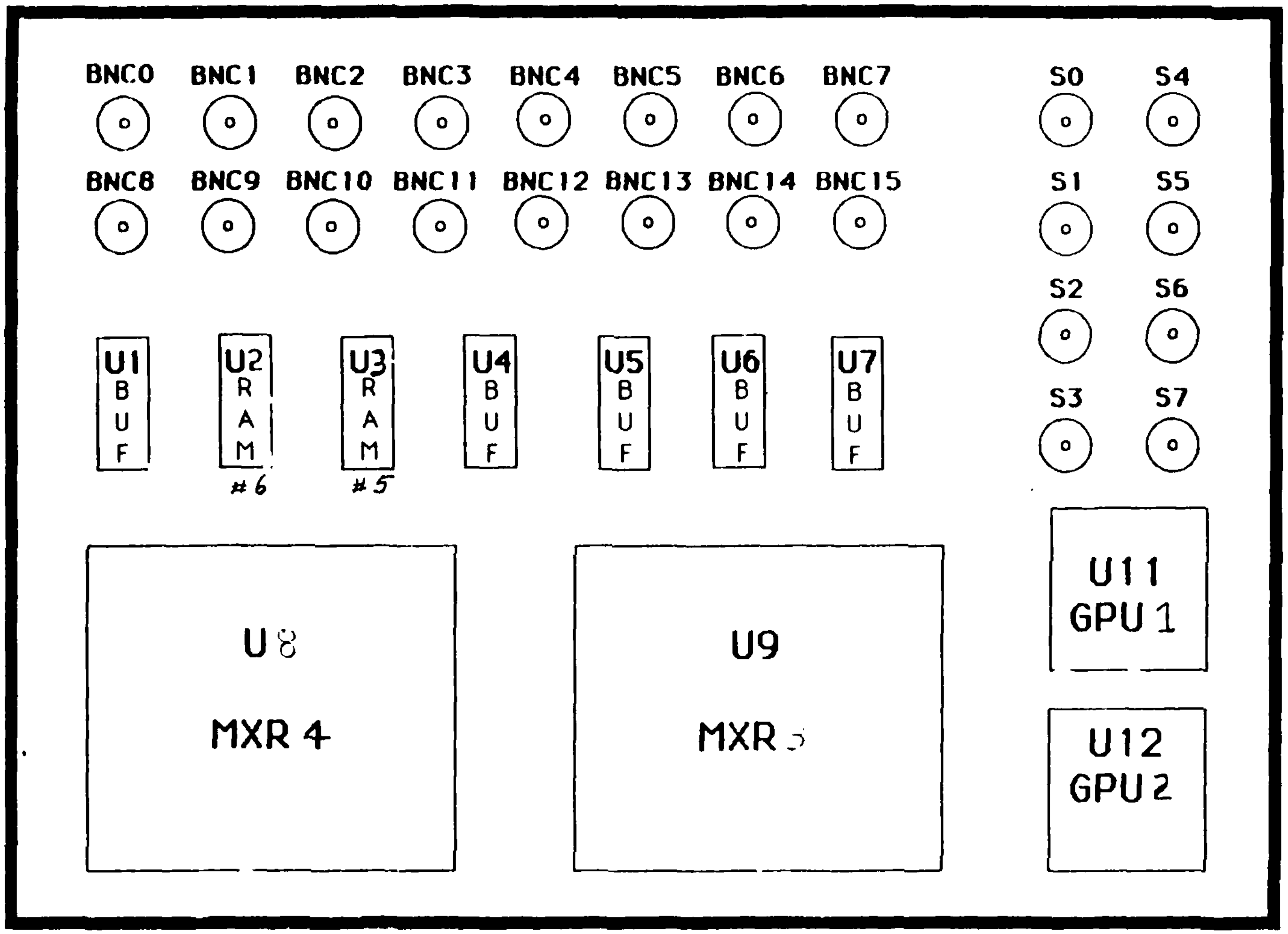
Introduction

Previous X-ray dose-rate tests of this same ALU board were reported in the literature(1). Dynamic and static upset rates of 9.8E11 and 1.7E11 rads/s were obtained. In those tests, the microprocessor (GP 001) was identified as the part responsible for upset of the subsystem. The objective of these tests was to continue the study and comparison of discrete device upset conditions vs those of an operating subsystem. Results will show that predictions of SEU insensitivity, based on device results, agreed with the subsystem results; whereas the proton induced upset of the microprocessor was predictable on the basis of parts test data but not the lack of recovery. The X-ray data(1) also disagreed with parts data(2) in that subsystem upset levels were higher than predicted.

Description Of Tests

The first heavy ion tests were carried out at the Bevalac facility of the Lawrence Radiation Lab., Berkeley, CA. The energy of the iron ions incident on the water column or Ridge Filter was 600 MeV/amu. A description of this setup can be found elsewhere(3). Two beam environments were used in the test. The Ridge Filter provided an iron spectrum with a maximum LET of 26 Mev-cm^2/mg and a total fluence of 2E6 particles/cm^2 with 4E3 p/cm^2 in the range of 23 to 26 MeV-cm^2/mg. This yielded an equivalent maximum LET of 52 MeV-cm^2/mg for an incident angle of 60°. The water column supplied particles with a LET of 6.5 and a maximum of 13 MeV-cm^2/mg at 60°. The test was dynamic with an operating voltage of 7 volts and a frequency of 2.0 MHz, thereby representing the worst case conditions for maximum SEU sensitivity. The test board layout is shown in Figure 1. All devices were CMOS/SOS with 5 micron feature sizes. They included 2 Gate Universal Arrays (MXRs, RCA TA 11093-BM1), 2 General Processor Units (RCA GP 001), 2 256X4 static RAMs (RCA CDP 1822), and 5 level shifting buffers (RCA CD 40116). The ion beam irradiated all parts simultaneously.

The functional block diagram of the ALU is shown in Figure 2. The first MXR generates the RAM address and serves as an incrementer. The CRABF switch controls which input (starting address or incrementer) is loaded into the RAM. This is the identical function that the MXR performs in the spacecraft



NOTE: DRAWING SIZE IS 3:4 SCALE

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Figure 1. Board Layout

SCP-STAR ALU Used in Flash X-ray Test

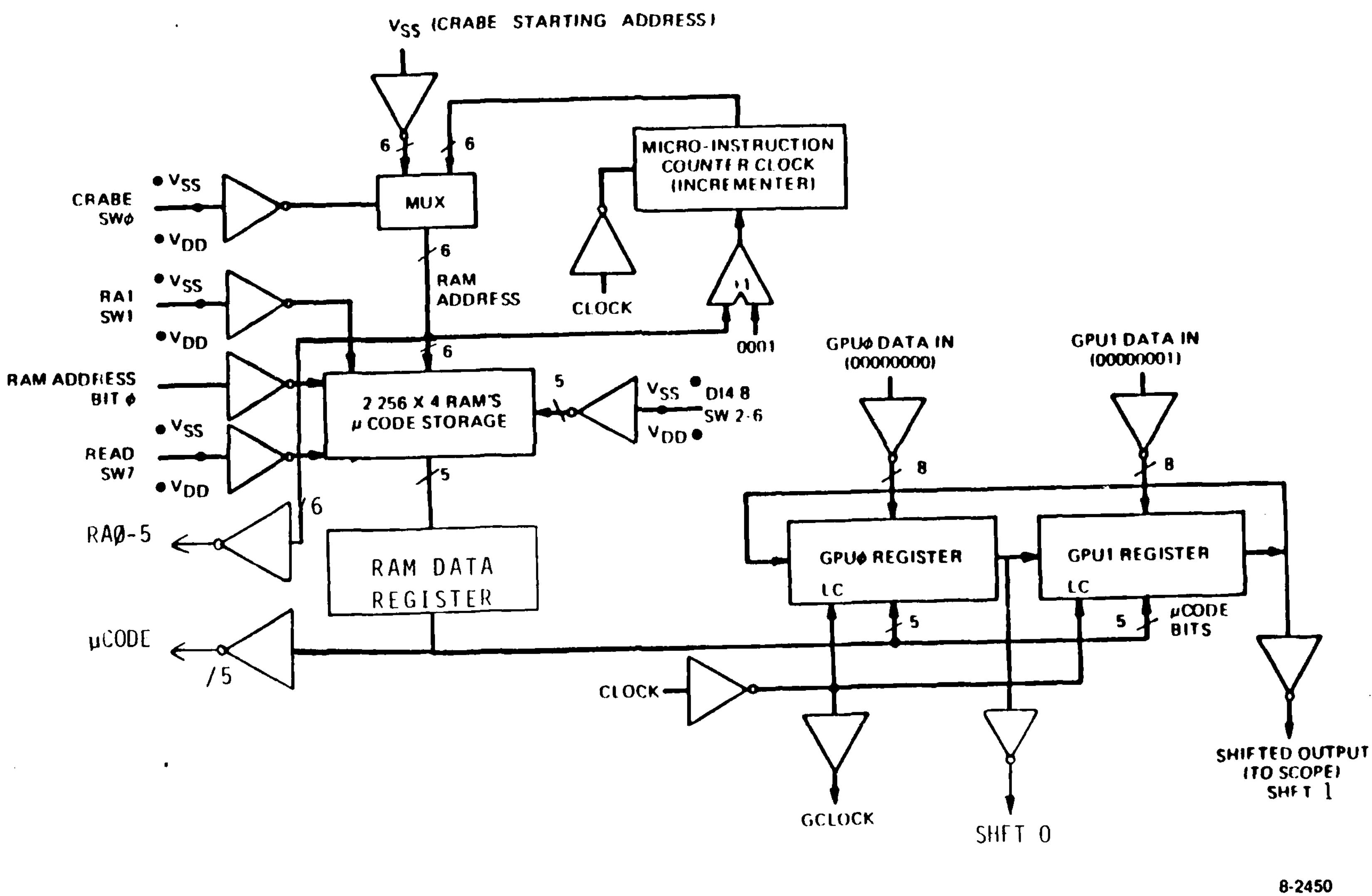

Figure 2. Functional Block Diagram

computer. The RAM is the same part that is used as a memory management page register in the computer. In this configuration, it is used to emulate the microcode ROM. The microcode as well as the operation of the RAM is controlled by switches. The second MXR is used as a register to emulate the memory data register of the computer. This data is then transferred to GPUs as control signals to determine the operation which the GPU will perform. The two 8-bit GPUs are concatenated to form a 16-bit register/ALU. The test consists of loading the GPU code for a LOAD instruction into address 0000H of the RAM. The code for a shift operation is then written into the remaining 255 locations of memory. The RAM is then switched into a read mode. The 16-bit register is loaded with 0001 Hex. The first MXR now increments a count which addresses the shift locations of memory. The GPU shifts the pattern such that a logical one appears on the output of the second GPU for every 16 clock cycles. Upset is indicated on a monitoring scope when a change in the ratio of the GPU output to the clock cycles occurred. This change in ratio only occurs when a 0-to-1 transition takes place. A 1-to-0 transition causes the GPU output to disappear. This condition is ambiguous since a hard device failure, for example the output driver, will produce the same result.

The Brookhaven Van de Graaff was used to provide 350 MeV gold ions with a LET of 83 at normal incidence, and a maximum of 243 MeV-cm^2/mg at 70°. This facility is the state-of-the-art in SEU testing and was originally designed by Van Gunten of NSA with support from Stassinopoulos of NASA, Goddard. Additional support has been provided by USASDC, DNA, and NRL. The large vacuum chamber permits system testing at the board and box level. Beam size restricted the irradiation to individual part types, namely, two microprocessors, two MXRs, and two RAMs. This is in contrast with the entire board exposure in the X-ray and also the Bevalac tests. Fluence measurements were made by means of 4 scintillation counters within the beam circumference, and ion beam species and energy by means of solid state detectors.

A beam weapon simulator has been established at Brookhaven under DNA sponsorship. This facility is called Radiation Effects Facility, (REF) and involves the time sharing of a 200 MeV proton beam provided by a LINAC. The beam sharing is with the Alternating Gradient Syncroton, (AGS) which uses the proton beam as its basic source of injected particles. Beam size restricted the irradiation to individual parts. The same three part types were exposed as in the SEU tests. Failure was indicated as before by a change in frequency ratio of the microprocessor output relative to the clock or simply, temporary or permanent loss of output. Operating voltage and frequency were 10 volts and 3 MHz for both SEU and proton tests. Dosimetry in the proton runs was provided by activation of Al and plastic foils. Proton pulse width was maintained at 10 μs except for the first exposure. Every 10 μs pulse contained 2000 micropulses of one nanosecond with a 5 ns period. Doses were accumulated by multiple 10 μs pulses at a rate of about one per second. Proton energy was fixed at 180 MeV for all runs.

Results

Figures 3 a, b, and c show the scope traces for the system clock (lower trace) and the shifted output (upper trace) for pre-exposure, post-exposure without the ridge filter, and then with filter. A similar set of traces were also obtained in the Brookhaven tests with gold ions. In contrast to the

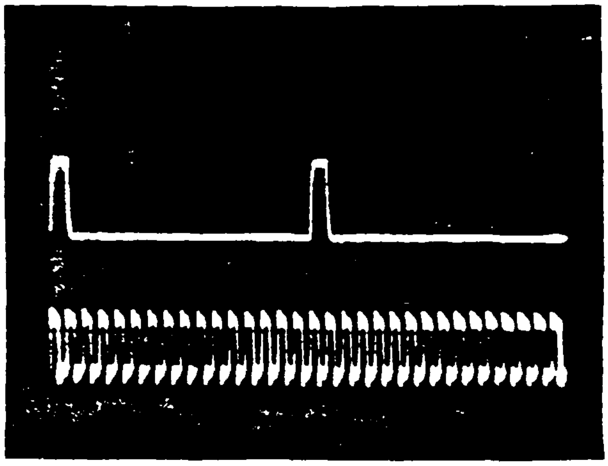

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Figure 3a. Pre-rad Output

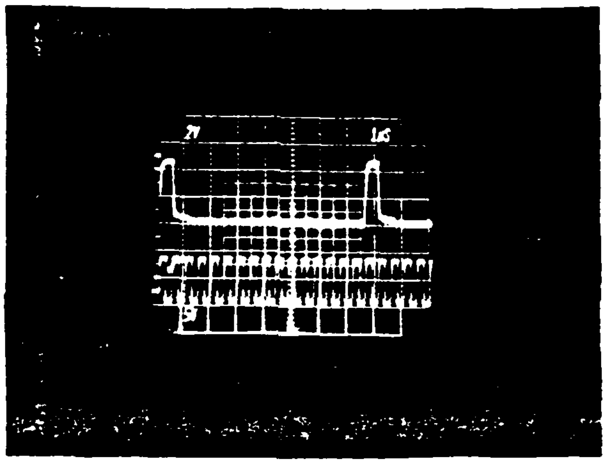

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Figure 3b. Post-rad No Filter

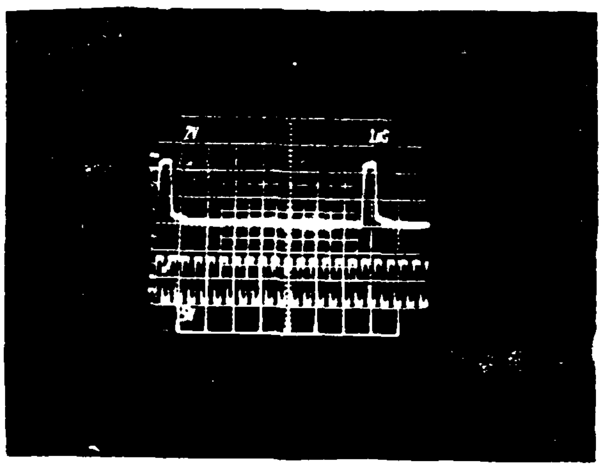

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Figure 3c. Post-rad with Ridge Filter

TABLE 1. TEST RESULTS FOR 350 MeV GOLD IONS

Sample Type	Fluence p/cm^2	Incident Angle	LET $MeV\text{-}cm^2/mg$	Comments
Micro(1)	7.4E6	40	108	No Upset
Micro(1)	4.8E6	60	167	No Upset
Micro(2)	8.2E5	30	96	No Upset
Micro(2)	7.3E5	40	108	No Upset
Micro(2)	7.3E6	40	108	No Upset
Micro(2)	4.8E6	60	167	No Upset
MXR(3)	3.3E6	70	243	No Upset
MXR(4)	3.4E6	70	243	No Upset
RAM(5)	3.3E6	70	243	No Upset
RAM(6)	3.3E6	70	243	No Upset

Bevalac tests, parts were irradiated one by one rather than all simultaneously and with much higher LET. Table 1 contains the results obtained with gold ion exposures.

Discussion

The technology used in the fabrication of the parts in the ALU subsystem is relatively old with feature sizes of 5 to 6 microns. These parts are now being made with 3 micron sizes. SEU data has been obtained(4) for the GP 001 microprocessor and the 1822 RAM. Both parts could not be upset with particles of LET greater than 75 and 216 MeV-cm^2/mg. On the basis of this data, upset of the ALU subsystem would not be expected during irradiation by gold ions at nearly normal incidence. As it turned out, the use of gold ions provided LET values up to 243 MeV-cm^2/mg at an angle of 70°. This means that the upset threshold LETs are greater than 167 for the microprocessor and 243 MeV-cm^2/mg for the MXR and RAM. The leadless chip carrier package prevented higher angles from being used. The corresponding limiting error cross sections are less than 3E-7 and 2E-7 cm^2.

As shown in Table 2, upset and failure of the subsystem took place when the microprocessor parts were exposed. A single pulse with a dose of 119 krads was sufficient to upset the timing and operation of the part to cause complete failure. Re-initialization of the circuit was necessary, however, in only one sample was this possible after a brief annealing period. This sample was exposed to another pulse and it failed without recovery occurring. The frequency was reduced two orders of magnitude in these measurements. In addition, all failed parts were tried again the following morning without success. Apparently, the equilibrium state of damage, namely, in timing loss did not permit operation in this circuit design. Cobalt 60 data taken with these parts(2) indicates about a 10% loss of speed for 119 krads; thus, based on low dose rate tests these failures were unexpected. In total contrast to these results, the MXR and RAM showed no sensitivity for failure up to doses of 60 and 18.9 megarads. The corresponding average dose rates, although for small sample sizes, were both in the low and high regimes as noted under comments in Table 2. The data appears to suggest that pulse delivered doses and their effects on some device designs may not be predicted on the basis of low dose rate data. However, high dose rate and dose/pulse data for the GP001 part was

TABLE 2. TEST RESULTS FOR 180 MeV PROTONS

Sample Type	# of Pulses	Pulse Width μs	Dose Rate Rads/s	Average Dose Rate Rads/s	Comments
Micro(1-A)	2	20	1.36E5	6.8E9	Fail 1 Pul. Replace No Recover
Micro(1-B)	1	10	6.21E4	6.2E9	Pass
Micro(2-A)	1	10	7.46E4	7.4E9	Pass
Micro(2-A)	3	10	1.38E5	1.4E10	Fail 1 Pul. Replace No Recover
Micro(2-B)	1	10	2.1E5	2.1E10	Fail 1 Pul. Recovered Reused
Micro(2-B)	1	10	2.1E5	2.1E10	Fail 1 Pul. No Recover Replace
Micro(2-C)	2	10	2.64E5	1.3E5	Fail 2 Pul No Recover Replace
Micro(2-D)	1	10	1.19E5	1.2E10	Fail 1 Pul No Recover Static Exp.
MXR(3)	1	10	9.21E4	9.2E9	Pass
MXR(3)	25	10	1.57E5	6.3E3	Pass
MXR(3)	750	10	6.03E7	8.0E4	Pass
MXR(4)	1	10	9.6E4	9.6E9	Pass
MXR(4)	25	10	1.9E6	7.6E4	Pass
MXR(4)	250	10	1.89E7	7.6E4	Pass
RAM(5)	1	10	6.27E4	6.3E9	Pass
RAM(5)	25	10	1.74E6	6.9E4	Pass
RAM(6)	1	10	9.55E4	9.6E9	Pass
RAM(6)	33	10	2.55E6	7.7E4	Pass
RAM(6)	250	10	1.87E7	7.6E4	Pass

NOTE: Numbers after sample type indicate sample position on board and letters indicate different samples.

previously obtained and reported in the literature(2). The mean dose for the loss of part output was measured to be 16.4 krads delivered in a 2 μs electron pulse. A dose/2μs-pulse of 18 krads produced a shutdown time of two microseconds which lengthened to 50 μs for 50 krads. Figure 4 taken from this previous work illustrates those results. It shows scope traces of two data outputs from the GP 001 microprocessor with a 10 μs shutdown and recovery of the 0 output and transient recovery of the second output. This result took place over a period of about 15 μs after irradiation by a 2.1 μs pulse of 10 MeV electrons. The dose/pulse was 21 krads. Recent tests (3/18/88, 25 days after Brookhaven) of the four failed units at GE Astro Space Division indicate that they are still not functioning in the system. The outputs of these parts are zero. It appears that 119 krads/pulse (1.2E10 rads/s) was adequate and effective in producing permanent failure of the microprocessor.

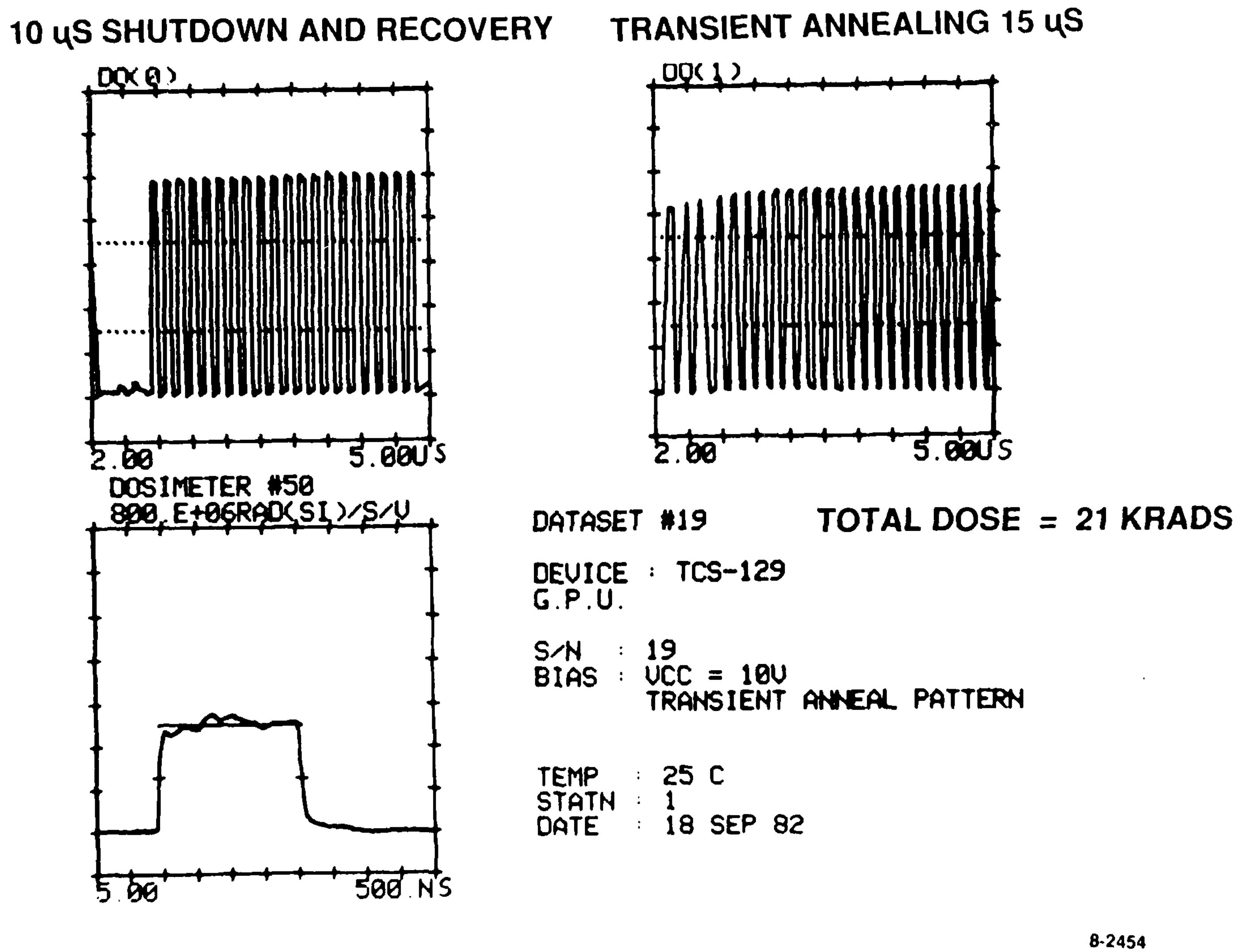

Figure 4. Outputs of GP 001 Microprocessor During Irradiation by 10 Mev Electrons with a Pulse Width of 2.0 μs and a Dose/Pulse of 21 krads

Twenty runs were made in the proton tests. Table 2 shows the results of these exposures. The average dose rate is based on the time to failure or the total time in any series of pulses and the corresponding dose. For example, in the first run the part failed after a single pulse, but two pulses were delivered before the beam could be shut-off; thus, half the total dose divided by 20 μs gives the average dose rate.

Conclusions

It can be concluded from these results that doses delivered at high dose rates of 180 MeV protons can produce system failure even though low dose rate data such as obtained with cobalt 60 sources predict no problem. This result is dependent on device and system designs and was not true for the MXR and RAM parts, only the microprocessor.

The parts data taken from SEU tests does successfully predict system operation without upset when it is irradiated with heavy ions of LET values in the range of 167 to 243 MeV-cm^2/mg.

References

(1) G. J. Brucker, K. K. Oey, M. Miller, and C. Kertesz, "Flash X-Ray Test Of The CMOS/SOS SCP-STAR ALU", IEEE Trans. on Nucl. Sci., Vol. NS-31, No. 6, Dec. 1984

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(3) T. L. Criswell, P. R. Measel, and K. L. Wahlin, "Single Event Upset Testing With Relativistic Heavy Ions", IEEE Trans. on Nucl. Sci., Vol. Ns-31, No. 6, Dec. 1984

(4) D. K. Nichols, W. Price, W. A. Kolasinski, R. Koga, J.C. Pickel, J. T. Blanford, and A. E. Waskiewicz, "Trends In Parts Susceptibility To Single Event From Heavy Ions", IEEE Trans. on Nucl. Sci., Vol. NS-32, No. 6, Dec. 1985

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